ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/47531199

Longitudinal changes in hearing sensitivity among men: The Veterans Affairs Normative Aging Studya)

ARTICLE *in* THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA · OCTOBER 2010

Impact Factor: 1.5 · DOI: 10.1121/1.3466878 · Source: PubMed

CITATIONS
6

READS
12

4 AUTHORS:

Katharina Victoria Echt
Emory University
38 PUBLICATIONS **494** CITATIONS

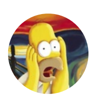
SEE PROFILE

Sherri L. Smith
U.S. Department of Veterans Affairs
27 PUBLICATIONS **218** CITATIONS

SEE PROFILE

Andrea Backsheider Burridge
University of Houston
22 PUBLICATIONS **115** CITATIONS

SEE PROFILE



Avron Spiro
Boston University
262 PUBLICATIONS **8,675** CITATIONS

SEE PROFILE

Available from: Sherri L. Smith
Retrieved on: 27 January 2016

Longitudinal changes in hearing sensitivity among men: The Veterans Affairs Normative Aging Study[a)]

Katharina V. Echt[b)]
Atlanta Veterans Affairs Medical Center, 1670 Clairmont Road (151/R), Decatur, Georgia 30033

Sherri L. Smith
James H. Quillen Veterans Affairs Medical Center, Audiology (126), Mountain Home, Tennessee 37684

Andrea Backscheider Burridge
Department of Educational Psychology, University of Houston, Houston, Texas 77204

Avron Spiro III
Veterans Affairs Boston Healthcare System, 150 South Huntington Avenue (151MAV), Boston, Massachusetts 02130

(Received 9 November 2008; revised 28 June 2010; accepted 30 June 2010)

Over 35 years (1962–1996), participants of the Veterans Affairs Normative Aging Study (NAS), a study of healthy aging in men, completed up to eight audiometric assessments. This report describes the age-related hearing trajectories of screened men ($n=953$) aged 23 to 81 years at enrollment, estimates the typical rate of change per decade in hearing sensitivity, and compares longitudinal and cross-sectional estimates of change in hearing sensitivity. The men were followed 14 years on average. The hearing trajectories, based on a mixed-effects model analytical approach to the data, provide converging evidence that hearing loss in aging is pervasive and progressive even among men initially selected for good physical health. Typically the men accrued early losses (>25 dB HL) in hearing sensitivity at the higher frequencies beginning in the early 40s, but maintained hearing thresholds better than 25 dB HL for lower frequencies into old age. The average rate of change per year across frequencies and age was 0.69 dB. Predicted cross-sectional estimates of change in hearing sensitivity reliably approximated longitudinal trajectories, with slight misestimations in the 8th decade. [DOI: 10.1121/1.3466878]

PACS number(s): 43.66.Sr, 43.66.Cb, 43.64.Wn [BCM] Pages: 1992–2002

I. INTRODUCTION

Greater prevalence of hearing loss with aging is a well-established fact in industrialized societies (e.g., Corso, 1958; Mościcki *et al.*, 1985; Cooper, 1994; Cruickshanks *et al.*, 1998, 2003; Helzner *et al.*, 2005). In the United States, hearing loss is the third most common chronic condition affecting older adults (Lethbridge-Cejku *et al.*, 2004). Approximately half of the 31.5 million Americans with hearing loss are age 55 years and older (Kochkin, 2005). As many as 83% of persons over the age of 70 years experience some degree of hearing loss (Cruickshanks *et al.*, 1998; Helzner *et al.*, 2005). Patterns of hearing sensitivity change with aging have been studied extensively using cross-sectional approaches (see Divenyi and Simon, 1999 and Nelson and Hinojosa, 2006 for reviews) and short-term longitudinal studies (e.g., Moller, 1981; Mościcki *et al.*, 1985; Pedersen *et al.*, 1989; Cruickshanks *et al.*, 2003; Davis *et al.*, 1991; Gates and Cooper, 1991; Ostri and Parving, 1991; Hietanen *et al.*, 2004).

Large scale studies provide converging evidence that (1) hearing loss increases with age; (2) the prevalence of hearing loss for men older than 60 years ranges from 31.0% (Mościcki *et al.*, 1985) to 45.9% (Cruickshanks *et al.*, 1998) depending on the definition of hearing loss applied; (3) higher prevalence rates (76.9%) of hearing loss are found at the mid to higher frequencies (2.0, 4.0, 8.0 kHz; Helzner *et al.*, 2005); and (4) men have poorer hearing sensitivity for higher frequencies than women. Nevertheless, current knowledge of changes in hearing sensitivity with aging is limited given the paucity of longitudinal evidence and the known problems of inferring change from cross-sectional differences. Brant and Fozard (1990), reporting Baltimore Longitudinal Study on Aging (BLSA) data, found that the cross-sectional rate of change in hearing thresholds (0.59 dB per year) underestimated the actual average longitudinal rate of change of 0.69–1.68 dB per year. Lee and colleagues (2005) examined pure-tone thresholds for 188 older adults, using a relatively large number of repeated measures (9.8) over a shorter duration (3–11.5 years) and found an average threshold increase of 1.0 dB per year at ages 60 and older. These findings, overall, suggest that hearing loss increases in older age groups.

The Baltimore Longitudinal Study of Aging (BLSA; Brant and Fozard, 1990; Pearson *et al.*, 1995) and the Veter-

[a)]Portions of this work were presented in "Longitudinal changes in hearing and effects on cognition and health management: The VA Normative Aging Study." *The Gerontological Society of America's* 59th Annual Meeting, Dallas, TX, November, 2006.

[b)]Author to whom correspondence should be addressed. Electronic mail: kecht@emory.edu

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

ans Affairs (VA) Normative Aging Study (NAS; Bell *et al.*, 1972) are both longitudinal studies of the aging process (Fozard *et al.*, 1990) that have measured hearing sensitivity with approximately 10 or more years of follow-up and with large samples of men of a broad age range. In particular, Brant and Fozard (1990) and Pearson *et al.* (1995) published audiometric data from the BLSA that described age-associated hearing loss in normal aging for both men and women. The BLSA men were followed over nine years on average, and up to 23 years. The BLSA investigators confirmed longitudinally the cross-sectional findings that older adults have greater hearing loss for higher frequencies than for lower frequencies and that hearing loss accelerates with age. These investigators further reported that changes in hearing thresholds in men occur as early as age 30 and that hearing levels and longitudinal changes became increasingly variable with age even in a select and relatively homogenous longitudinal study sample. With the exception of a study by Lawrence *et al.* (2001) relating hearing loss to dental status, longitudinal data on hearing sensitivity from the NAS men have not been reported previously.

The purpose of this report is to build on, and extend, the BLSA findings for men by describing longitudinal changes in hearing sensitivity in NAS participants. In contrast to the BLSA, the NAS data are based on a larger sample of men who were followed approximately 5 years longer (average 14 years; maximum 33 years). The NAS differed from the BLSA in that participants were screened for good health at the time of enrollment and a broader socioeconomic and education range was included.

The primary aims of this article were as follows: (1) to describe the hearing trajectories of men over time, (2) to estimate the typical rate of change per decade in hearing sensitivity, and (3) to compare longitudinal and cross-sectional estimates of change in hearing sensitivity.

II. METHOD

A. Study population

The VA NAS is a longitudinal study of aging in initially healthy men established at the Boston VA Outpatient Clinic in 1963 (Bell *et al.*, 1972). Over 6 000 potential participants were recruited from the community and screened for good general health (Bossé *et al.*, 1984; Damon, 1969). Men (N =2,280) aged 21 to 81 years (M=42.8; SD=9.5) were enrolled. Most men (76%) were 35 to 64 years old at the time of enrollment and nearly all were Caucasian. Fewer than 2% of the participants were African-American, which is less than the corresponding 3.7% African-American population for metropolitan Boston in 1970 (Bossé *et al.*, 1984). Most of the participants (86%) had a high school diploma and 26% were college graduates. Compared to the general Boston population, the participants were from higher socioeconomic strata. At the time of enrollment in the NAS, 23% percent of the participants were employed in professional or technical occupations (e.g., engineers, medical technicians), 21% were managers or proprietors, 16% were skilled craftsmen (e.g., electricians, plumbers), 8% clerical or sales workers, and 28% were service workers (mostly policemen and firemen, but also postal couriers, janitors, etc.). Only 4% of the participants were operatives (e.g., factory workers, delivery drivers) or laborers (e.g., manual laborers, farmers). As is characteristic of many men born during the first third of the 20th century, the majority of the participants (>90%) served in the military, and 44% of the participants saw combat (most in WW II, some in Korea, and a few in Vietnam). Bossé *et al.* (1984) provide a detailed description of the NAS sample.

Once enrolled, the participants reported to the NAS testing location based at the Boston VA Outpatient Clinic for thorough examination, including audiometric assessment. Until 1984, men were assessed every 3 (age$\geq$52) or 5 (age$<$52) years; thereafter until 1996 (when audiometric testing ceased), all men were assessed every 3 years. Between 1962 and 1996, a total of 2 169 men received one or more such assessments, generating a total of 17 094 audiograms on the 4 338 ears. At each NAS exam, the men provided written informed consent.

Participants were excluded from the present study if an audiometric assessment at any time of measurement suggested evidence of hearing loss due to other than age-related causes, including at the first visit. The following exclusion criteria, akin to those of Pearson *et al.* (1995), were adopted to facilitate comparisons between BLSA and NAS data and included: (1) unilateral loss (criterion: mean threshold at 0.5, 1.0, 2.0, and 4.0 kHz that differed between ears by more than 10 dB HL at any visit), (2) conductive or mixed hearing loss (criterion: air-bone gap that was greater than 15 dB HL at two consecutive frequencies at any visit), or (3) evidence of noise-induced hearing loss (criterion: notch in the audiogram of either ear where the threshold at 3.0, 4.0 or 6.0 kHz, if 3.0 or 6.0 kHz were available, was more than 15 dB worse than at both 2.0 and 8.0 kHz at any visit (Ward, 1980; Kryter, 1985; Pearson *et al.*, 1995). Individuals who were missing data (n=27) at either 2.0 or 8.0 kHz at any visit were excluded due to inability to determine evidence of noise-induced hearing loss in the audiogram. Similar to Pearson *et al.* (1995), who excluded 45% of the BLSA sample with these criteria, of the 2 169 NAS men who took an audiometric test, 1 216 (56.1%) were excluded due to evidence of one or more of these types of hearing loss at *any* visit, leaving 953 men in the final screened sample. Among those excluded, 485 men (22%) had evidence of unilateral loss, 144 (7%) had evidence of a conductive component, and 899 (41%) were excluded due to evidence of noise-induced hearing loss. Many (n=310) of these individuals had evidence of multiple types of hearing loss (e.g., noise induced *and* unilateral loss). Six-hundred-fifty-six individuals had evidence of noise-induced hearing loss singly, with no co-occurrence of unilateral loss or of conductive component.

B. Screened sample

Descriptions and data will henceforth be limited to the final screened sample (n=953) which represents initially healthy men who at each study visit were free of otologic abnormalities and audiometric noise notches based on the above criteria. Detail regarding the longitudinal follow-up

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

TABLE I. Characteristics (mean, minimum, and maximum) of the longitudinal follow-up for men in each age group at the first visit for the final screened sample ($n=953$).

Age group	<30			30–39			40–49			50–59			60–69			70–79			80–89		
n	55			275			351			208			46			15			3		
	M	Min	Max	M	Min	Max	M	Min	Max	M	Min	Max	M	Min	Max	M	Min	Max	M	Min	Max
Yrs. of follow-up	11.7	0	29	15.2	0	29	16.1	0	31	13.0	0	33	10.2	0	26	4.1	0	16	4.3	0	8
No. of visits	2.9	1	6	3.7	1	7	4.0	1	8	3.5	1	8	3.0	1	8	1.9	1	5	2.0	1	3
Visit interval (yrs.)	4.3	2	7	4.4	2	9	4.2	1	15	3.8	1	8	3.6	2	7	3.0	2	4	2.6	2	3

for the sample is given in Table I, which lists the mean, minimum, and maximum number of years the men were followed, the number of visits, and the mean number of years between each visit (visit interval) for each decade of age at the first visit.

The majority of the men (87.5%) entered the study between the ages of 30 and 59 years and these individuals had the greatest number of assessments. Men who entered the study at ages less than 30 or age 60 or older had the fewest number of assessments. The majority of the men (69.9%) were followed for at least 9 years. Overall, the men had an average of 14.4 years of follow-up (range: 0–33), 3.6 visits (range: 1–8), and 4.1 years between the study visits (range: 1–14.5), which resulted in a total of 6 956 audiograms on 1 906 ears. Owing to small sample size (and consequent high standard errors) for the relatively few men who entered the study in their 3rd and 9th decades, further findings specific to these age groups are not reported.

Table II displays the distribution of the number of years the men were followed once enrolled in the study, by their age decade at entry. The bottom row depicts the total number of men in the initial age group and the far-right column depicts the total number of men who were followed for a given range of years. There were two men who were followed for 30 years or more, one of whom enrolled in the study in his 40s and the other who entered the study in his 50s. Five-hundred-fifty-one of the 953 men in the final sample were followed for 15 years or more and 454 were followed for 18 years or longer.

The mean age at first visit was 44.1 years ($SD=10.2$) and 97.4% were Caucasian. The majority of the men had at least some college education (37.7% had some college experience, 15.9% were college graduates, and 16.6% had graduate-level education) and 19.4% were high school graduates with no further education. The occupation distribution of the men in the screened sample is listed in Table III. At NAS enrollment, the majority of men were employed in civilian occupations consistent with low noise exposure. Approximately 23.1% of the men were categorized as having occupations with potential exposure to intense noise (e.g., policemen, firemen, operatives, laborers); however, the proportion of these men who were actually exposed to intense noise is unknown. Occupations such as postal couriers and janitors, for instance, as part of NAS protocols were grouped with potentially noisy occupation categories, but most likely these were not high-level noise occupations. The majority (87%) of the men in the screened sample served in the military during wartime.

C. Apparatus and procedures

Audiologists on the VA Outpatient Clinic staff completed audiometric evaluations of participants at each visit, and participants underwent an otologic evaluation by an otologist. Pure-tone testing was conducted using three audiometers from 1962 through 1996 (Beltone 15C, and Grason-Stadler models 1701 and 10). The audiometers were calibrated to the standard used at the time by a certified technician on an annual basis at the minimum and the staff audiologists performed daily inspections and listening

TABLE II. Distribution of the number of years the men were followed from the starting age interval.

	Starting age interval							
Yrs. follow-up	20–29	30–39	40–49	50–59	60–69	70–79	80–89	Total n
0–2.9	17	53	47	40	12	8	1	178
3–5.9	3	11	21	22	3	2	1	63
6–8.9	5	12	13	9	4	2	1	46
9–11.9	4	20	20	18	9	2	0	73
12–14.9	6	10	14	10	2	0	0	42
15–17.9	1	21	41	27	6	1	0	97
18–20.9	4	26	50	27	3	0	0	110
21–23.9	3	72	75	38	4	0	0	192
24–26.9	7	37	55	13	3	0	0	115
27–29.9	5	13	14	3	0	0	0	35
30–32.9	0	0	1	0	0	0	0	1
33	0	0	0	1	0	0	0	1
Total n	55	275	351	208	46	15	3	953

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

TABLE III. Occupation distributions at the first visit for the men in the final screened sample ($n=953$).

Occupation	n	Percent
Professional/technical	244	26.6
Manager/proprietor	211	22.1
Clerical/sales	78	8.0
Skilled/craft	121	12.7
Service	236	24.8
Policeman	(119)	(13.0)
Firefighter	(76)	(8.3)
Operatives		
(Driver, factory worker)	18	2.0
Manual laborers	5	0.5
Unspecified (missing)	40	4.2

The numbers in parentheses represent the number of and proportion of policemen and firefighters who were part of the service occupation sector.

checks on the audiometric equipment. During the period reported here, the audiometers were calibrated to audiometric zero in accordance to four standards. Before July 1966, the American Standards Association (1951) was used, followed by the International Standards Organization (ISO, 1964) between 1966 and 1969, followed by the standards established by the American National Standards Institute (ANSI, 1969; 1989). Corrections were made to the data to account for minor differences in calibration.

Air-conduction thresholds were obtained for frequencies of 0.25, 0.50, 1.0, 2.0, 4.0, and 8.0 kHz and for octave frequencies from 0.25 through 4.0 kHz for bone conduction, for each ear. Air-conduction thresholds were obtained for 3.0 and 6.0 kHz in cases where the difference between the adjacent octave frequencies was 20 dB or greater. Thresholds were determined using pulsed tones and standard psychophysical testing procedures (Hirsh, 1952; Carhart and Jerger, 1959). All threshold levels are reported in dB Hearing Level (dB HL, ANSI, 1989). All audiologic testing was accomplished while the participant was seated in a double-walled sound suite (Industrial Acoustics Co., Bronx, NY).

D. Analytical approach

A variety of analytical approaches have been used to model longitudinal data on changes in hearing thresholds. In one of the more basic approaches, Lee *et al.* (2005) used linear regression to model the hearing data for each participant at each frequency for each ear individually, and then calculated the correlations among the regression parameters. A benefit of this approach is that the interpretation is simple; however, the use of independently estimated regression models does not adequately accommodate the unique aspects of longitudinal data, including how multiple observations on a given person are related, nor the potential bias produced by missing data, which often are characteristic of longitudinal data sets (Brant and Pearson, 1994). A second approach, used by Wiley *et al.* (2008), combined a curve-fitting procedure with Generalized Estimating Equation (GEE) methods to relate hearing thresholds over a 10-year period. The GEE approach provides robust estimates of population average effects, which is useful for making inferences about group differences, but does not allow for estimation of individual variation in initial hearing thresholds and the rates of decline.

A third approach, which has been used extensively in modeling the BLSA data (Brant and Fozard, 1990; Pearson *et al.*, 1995), is the mixed-effects model. Mixed-effects models can be used to fit longitudinal data in which the number and spacing of observations vary among the participants, and in contrast to other approaches, mixed-effects models can include participants with only a single observation (Goldstein, 1995; Singer and Willett, 2003). Mixed-effects models allow estimation of the average intercept and rates of change via the fixed effects, and for individual deviation via estimation of random effects using all data from all participants at all times of measurement, provided that there is a large sample size and large number of observations. The random effects account for individual variation in initial threshold, ear, differences in thresholds among the frequencies, and the patterns of longitudinal change. These random effects, in addition, account for the autocorrelation owing to repeated measurements on individuals and allow for unbalanced data in which individuals have different numbers of observations (i.e., missing thresholds at certain frequencies at a given visit) measured at different intervals.

When fitting a mixed-effects longitudinal model for change, the observed data for each participant are assumed to represent a random sample from their true hearing trajectory. All observations for every participant are retained in the analysis, contributing information to the estimation of the regression parameters at the times for which they contribute data. In the BLSA analyses, mixed-effects modeling was used to estimate hearing thresholds as a complex function of frequency, ear, age, and time.

In the mixed-effects model presented in Pearson *et al.* (1995) and replicated here, longitudinal change is represented by fixed linear and quadratic effects of time; cross-sectional age differences are represented by linear, quadratic, and cubic effects of age at first visit; and the audiometric configuration is represented by linear, quadratic, and cubic terms of the natural log of the frequency. To reduce multicollinearity, study time and age at first visit were centered (that is, time/age for a given individual were transformed by subtracting the respective means) at 10 and 44 years, respectively. Terms representing ear and visit (to contrast first versus subsequent visits) also were included. Two- and three-way interactions among age, time, and frequency were included to allow the longitudinal patterns of change to vary with age of entry and to allow the rates of change in thresholds to vary at different ages and frequencies. To account for individual variation in rates of change, in addition to a random intercept, seven random effect terms involving ear, time and frequency were included: a main effect for ear, log frequency terms up to the cubic, and time up to the quadratic.

In summary, the mixed-effects model assesses longitudinal change for the sample as a whole in both ears and across all frequencies (based on the fixed effects portion of the model), while accounting for individual differences around the overall hearing trajectory by including subject-specific random effects. An advantage of using the mixed-effects model approach is that each threshold estimated from the

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

TABLE IV. Fixed effects coefficients of the final mixed model.

Effect	Estimate	SE	*df*	*t* value	*p*
Intercept	425.150	20.191	949	21.06	<0.0001
Left ear	0.420	0.134	952	3.13	0.0018
Time	−8.271	2.232	51 000	−3.71	0.0002
$Time^2$	0.017	0.008	51 000	2.15	0.0319
Log(fr)	−159.590	8.537	51 000	−18.69	<0.0001
Log^2(fr)	18.852	1.187	51 000	15.89	<0.0001
Log^3(fr)	−0.651	0.054	51 000	−11.98	<0.0001
Age	−0.193	2.113	949	−0.09	0.9272
Age^2	−0.429	0.141	949	−3.05	0.0024
Age^3	0.026	0.007	949	3.99	<0.0001
Visit	−177.090	42.371	51 000	−4.18	<0.0001
Time*Age	0.016	0.024	51 000	0.68	0.4975
Time*Age^2	−0.010	0.002	51 000	−5.09	<0.0001
Time*Age^3	0.000	0.000	51 000	−2.18	0.0291
Time*Log(fr)	4.323	0.942	51 000	4.59	<0.0001
Time*Log^2(fr)	−0.732	0.131	51 000	−5.59	<0.0001
Time*Log^3(fr)	0.041	0.006	51 000	6.88	<0.0001
$Time^2$*Age	0.001	0.001	51 000	2.68	0.0073
$Time^2$*Age^2	0.000	0.000	51 000	1.64	0.1018
$Time^2$*Log(fr)	0.000	0.001	51 000	−0.33	0.7429
Log(fr)*Age	0.592	0.894	51 000	0.66	0.5077
Log(fr)*Age^2	0.179	0.060	51 000	3.01	0.0026
Log(fr)*Age^3	−0.012	0.003	51 000	−4.23	<0.0001
Log(fr)*Visit	75.398	17.929	51 000	4.21	<0.0001
Log^2(fr)*Age	−0.168	0.124	51 000	−1.35	0.1756
Log^2(fr)*Age^2	−0.024	0.008	51 000	−2.93	0.0034
Log^2(fr)*Age^3	0.002	0.000	51 000	4.44	<0.0001
Log^2(fr)*Visit	−10.605	2.494	51 000	−4.25	<0.0001
$Time^2$*Log(fr)*Age	0.000	0.000	51 000	−2.65	0.0079
$Time^2$*Log(fr)*Age^2	0.000	0.000	51 000	−1.68	0.0931
Log^3(fr)*Age	0.013	0.006	51 000	2.36	0.0183
Log^3(fr)*Age^2	0.001	0.000	51 000	2.83	0.0046
Log^3(fr)*Age^3	0.000	0.000	51 000	−4.61	<0.0001
Log^3(fr)*Visit	0.490	0.114	51 000	4.29	<0.0001
Time*Log(fr)*Age	−0.004	0.007	51 000	−0.52	0.6008
Time*Log(fr)*Age^2	0.003	0.001	51 000	5.85	<0.0001
Time*Log^2(fr)*Age	0.001	0.000	51 000	1.18	0.2397
Time*Log^2(fr)*Age^2	0.000	0.000	51 000	−6.38	<0.0001

Effect Terms: Time=time since first visit, Log(fr)=natural logarithm of the frequency in kHz, Age=age at first visit to represent cross-sectional age differences.

model is based on observed data included in the *entire* screened data set (i.e., all thresholds from all frequencies at both ears obtained from all participants at all visits). A second advantage is that the model accounts for missing threshold data in instances where inter-octaves frequencies were not tested at a time of measurement. This model has a disadvantage in that the presence of higher-order interaction terms makes interpretation more challenging. Because one goal of this paper was to predict changes in hearing thresholds over time, similar to Pearson *et al.* (1995), the additional terms were included. The threshold levels predicted from the model were then used to estimate the age-related hearing trajectories over time and to describe the rates of change in hearing thresholds for the sample over the course of the study. To obtain cross-sectional estimates of "change" in hearing sensitivity, the mixed-effects model was modified to omit the terms involving time and only the data from the first visit of the participants were analyzed.

III. RESULTS

After initially fitting the full model described above, non-significant terms were eliminated. The final model contained 38 fixed effects (the coefficients appear in Table IV) and also contained seven random effects: intercept, ear, log frequency terms up to the cubic, and time up to the quadratic. These random effects indicate that there was a significant degree of between-subject variability in hearing thresholds and in longitudinal change in thresholds over time (likelihood-ratio tests for the inclusion of these random effects gave p values <0.0001).

Across the frequencies measured, hearing sensitivity was symmetrical between the ears; however, the right ear

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

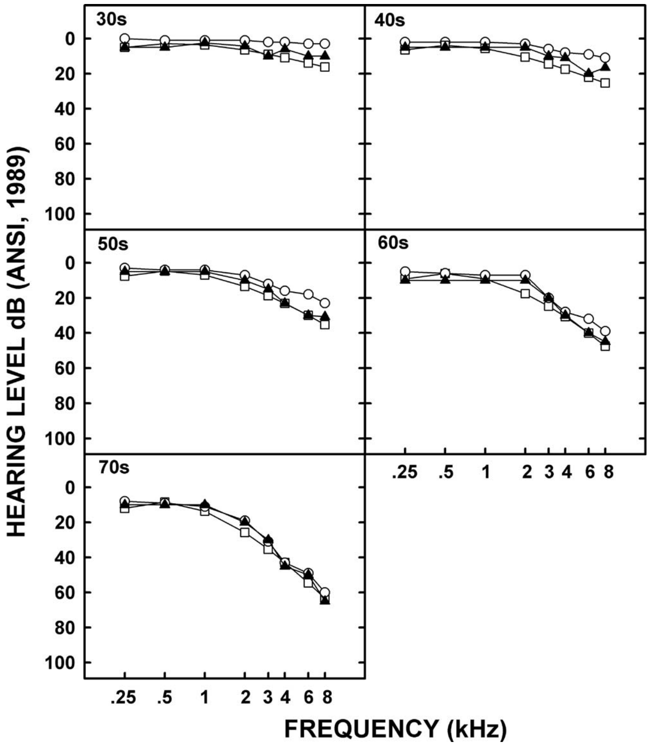


FIG. 1. Panels present, by decade, the median observed hearing threshold data for the final screened sample (filled triangles) and the thresholds estimated by the mixed-effects models (open squares). The ISO-7029 (2000) median hearing threshold data (open circles) are presented for comparison. The numbers of observations contributing to the thresholds for each frequency for each age group are listed in Table V.

estimated thresholds were slightly better on average (0.42 dB) than the thresholds for the left ear. Because there was no meaningful difference between the estimated thresholds for the two ears, the data from the right ear only are presented throughout to avoid redundancy. The estimated thresholds for the left ear can be obtained by adding 0.42 dB to the estimated thresholds for the right ear.

Unlike other statistical approaches used to model longitudinal changes, there are no easily-interpretable measures for goodness of fit for mixed-effects models (e.g., analog of R^2 estimate in regression models). The thresholds estimated from the model (open squares) and the observed median thresholds (filled triangles) obtained from the men for each age group are shown in Fig. 1, to illustrate that the model fitted the data adequately. The observed audiograms were based on median thresholds obtained from men aged ± 1 year of the initial age for each decade ($4^{th}-8^{th}$). For example, for the 40 year olds, the observed audiograms were taken as the median thresholds obtained from all men with measurements at ages 39–41 years. As seen in Fig. 1, the estimated and observed audiograms are similar for each age group. See Table V for the distribution of the observed thresholds. For comparison, Fig. 1 also displays, in each panel (open circles), the median thresholds from men based on the ISO-7029 standard (ISO, 2000), which are identical to Annex A in ANSI S3.44 (ANSI, 1996), and will be discussed later. Because the model fitted the observed data well, thresholds estimated from the model will be presented in the sections that follow.

A. Hearing thresholds

Figure 2 presents the estimated audiometric trajectories for each age group (i.e., 30s, 40s,…, 70s) at initial testing and over 15 years of follow up. The 30s–70s panel at the bottom right illustrates the estimated audiograms based on the data for the first visit. In each age group panel, the top line represents the initial estimated audiogram for men in that age group, and the successive lower lines are the estimated audiograms at 3-year intervals, with the bottom line representing the estimated audiogram of the same men 15 years later. The data indicate a marked increase in hearing thresholds evident at frequencies of 1.0 kHz and above, particularly for the older ages (e.g., 70 years), suggesting that hearing loss accelerates with increasing age, particularly for higher frequencies. This is particularly apparent in the comparison of the 30s–70s estimated audiograms within the bottom right panel of the figure.

Table VI details the mean threshold data with standard errors across frequency and age as estimated by the model for the frequencies from 0.25 through 8.0 kHz for a 10-year period from age at first visit in 5-year follow-up increments. The estimated thresholds for the frequency and age at which hearing loss (>25 dB HL) first occurred appear in bold. As expected, estimated hearing thresholds increased with age, particularly for frequencies above 2.0 kHz. Higher frequencies were affected earlier in life, mid-frequency thresholds were affected later in life, at around age 60, while low-

TABLE V. The 90^{th}, 50^{th}, and 10^{th} percentile thresholds (dB HL, ANSI, 1989) calculated from the observed data. Refer to Figure 1 for the median observed hearing threshold data (filled triangles).

	30s (±1 Yr.)				40s (±1 Yr.)				50s (±1 Yr.)				60s (±1 Yr.)				70s (±1 Yr.)			
kHz	*n*	90th	50th	10th	*n*	90th	50th	10th	*n*	90th	50th	10th	*n*	90th	50th	10th	*n*	90th	50th	10th
0.25	64	0	5	10	195	0	5	10	302	0	5	15	308	0	10	20	155	5	10	25
0.5	64	−1	5	10	195	0	5	14	302	0	5	15	308	0	10	20	155	0	10	20
1.0	64	0	3	10	195	0	5	15	302	0	5	15	308	0	10	20	155	5	10	25
2.0	64	−5	4	14	195	−2	5	15	302	0	10	25	308	0	10	30	155	5	20	40
3.0	17	0	10	30	117	0	10	35	228	5	15	50	284	5	20	50	148	15	30	55
4.0	64	0	6	25	195	1	11	51	302	5	23	56	308	10	30	60	155	20	45	65
6.0	14	0	10	75	96	5	20	65	206	10	30	65	271	15	40	75	144	20	50	75
8.0	64	0	10	35	195	5	17	62	302	10	31	70	308	20	45	80	155	30	65	85

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

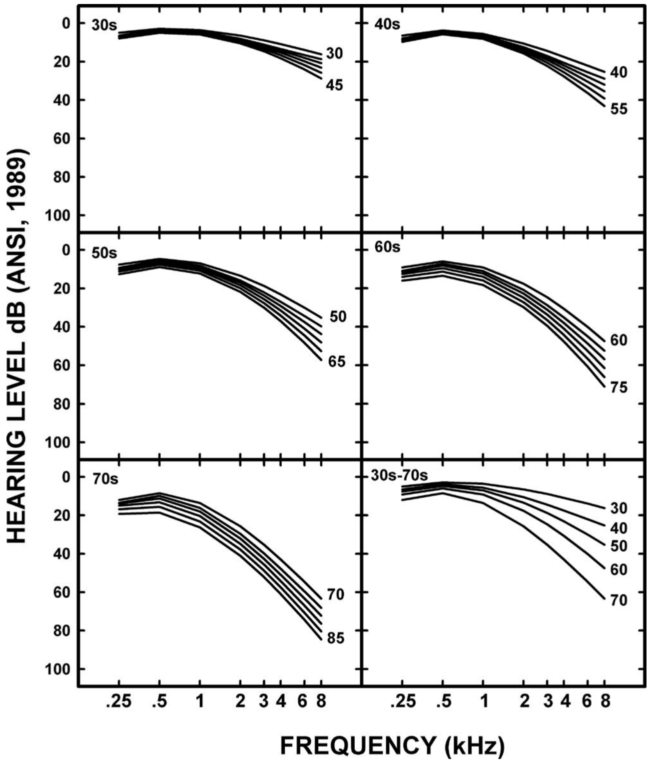


FIG. 2. The panels present, by decades 30–70, the progression of the mixed-effects model (estimated) audiometric thresholds (in dB HL, ANSI, 1989) in 3-year increments (total of 6 per panel: i.e., 30, 33, 36, 39, 42, 45) spanning 15 years. The top line in each panel shows the estimated initial visit thresholds for the ages 30s, 40s,…70s, and also appears in the 30s–70s panel (bottom right) to summarize the findings for each decade grouping.

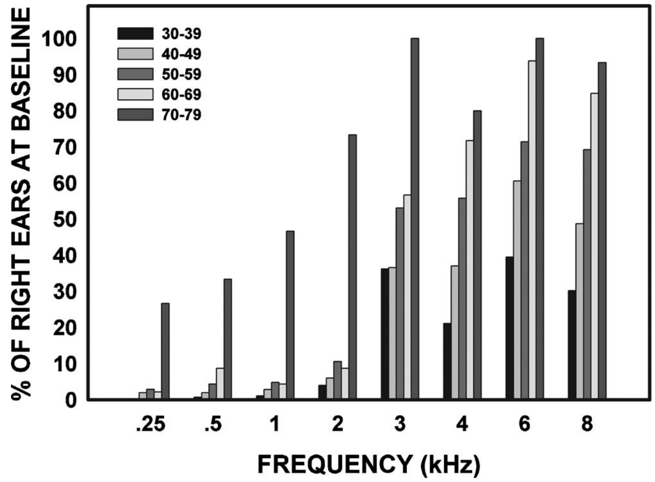


FIG. 3. The percent of modeled right-ear thresholds >25 dB HL (ANSI, 1989) for age decade groups using first visit estimated audiometric thresholds only.

frequency thresholds changed little with age. Hearing loss was evident at 6.0 and 8.0 kHz in the 40s, at 4.0 kHz in the mid-50s, at 3.0 kHz in the 60s, and at 2.0 kHz in the late 60s. The ages at which the modeled hearing thresholds were first >25 dB HL were 40, 43, 51, 59, and 70 years of age for frequencies of 8.0, 6.0, 4.0, 3.0, and 2.0, respectively. For 0.25, 0.5 and 1.0 kHz, estimated mean thresholds approached, but did not exceed, 25 dB HL. Standard errors ranged from 0.7 to 4.9 dB. The standard errors were lowest for estimated thresholds for lower frequencies and younger ages and highest for estimated thresholds for higher frequencies and ages, as expected.

The percentage of participants in each age decade who had estimated right ear hearing thresholds greater than 25 dB HL, as modeled using data for the first visit, is presented in Fig. 3 as a function of frequency. As expected, the onset of hearing loss (i.e., thresholds greater than 25 dB HL) affected fewer of the participants at the younger age decades and the greatest proportion of participants at the older decades. For each frequency, the percentage of participants who had estimated thresholds above 25 dB HL increased with each decade, particularly for the higher frequencies. In fact, approximately 20% of men in the 4th decade had hearing loss at 4.0

TABLE VI. Mean hearing thresholds (in dB HL, ANSI, 1989) and standard errors estimated by the mixed-effects model for men (n=953) aged 30 to 70 years at their first visit and their ages at longitudinal follow-up (5-year increments). The thresholds in boldface indicate the age at which the threshold first exceeded 25 dB HL, or 'normal hearing sensitivity', for the given frequency.

		0.25 kHz		0.5 kHz		1.0 kHz		2.0 kHz		3.0 kHz		4.0 kHz		6.0 kHz		8.0 kHz	
Age at first visit	Age at follow-up	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
30	30	5.0	1.1	2.9	1.3	3.6	1.5	6.5	1.9	8.9	2.1	10.9	2.3	14.0	2.5	16.2	2.8
	35	6.5	1.1	3.3	1.3	4.3	1.5	8.2	1.9	11.4	2.1	13.9	2.3	17.6	2.5	20.1	2.8
	40	6.9	1.1	3.8	1.3	4.8	1.5	9.0	1.9	12.7	2.1	15.7	2.3	20.4	2.5	24.1	2.8
40	40	6.5	0.7	3.8	0.8	5.6	1.0	10.6	1.2	14.5	1.3	17.5	1.5	22.0	1.6	**25.3**	1.8
	45	8.0	0.7	4.2	0.8	6.3	1.0	12.7	1.2	17.6	1.3	21.5	1.5	**27.0**	1.6	30.9	1.8
	50	8.5	0.7	4.6	0.8	6.9	1.0	13.8	1.2	19.6	1.3	24.2	1.5	31.3	1.6	36.7	1.8
50	50	7.6	0.7	4.7	0.8	6.9	1.0	13.4	1.2	18.8	1.3	23.1	1.4	30.0	1.6	35.3	1.8
	55	9.5	0.7	5.7	0.8	8.5	1.0	16.6	1.2	23.2	1.3	**28.4**	1.4	36.5	1.6	42.5	1.8
	60	10.6	0.7	6.9	0.8	10.0	1.0	18.9	1.2	**26.3**	1.3	32.4	1.4	42.1	1.6	49.6	1.8
60	60	9.2	1.2	6.0	1.4	9.1	1.7	17.6	2.0	24.7	2.2	30.7	2.4	40.1	2.7	47.5	3.0
	65	11.3	1.2	7.8	1.4	11.9	1.6	22.1	2.0	30.4	2.2	37.1	2.4	47.5	2.7	55.5	3.0
	70	13.0	1.2	10.1	1.4	14.6	1.6	**25.6**	2.0	34.7	2.2	42.1	2.4	54.0	2.7	63.2	3.0
70	70	12.0	2.0	8.4	2.3	13.6	2.7	25.7	3.3	35.3	3.7	42.9	4.0	54.6	4.5	63.3	4.9
	75	13.7	1.9	10.7	2.3	17.4	2.7	31.2	3.3	41.7	3.7	49.9	4.0	62.0	4.5	70.9	4.9
	80	15.5	2.0	13.9	2.3	21.3	2.8	35.8	3.3	46.7	3.7	55.2	4.1	68.2	4.5	77.8	4.9

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

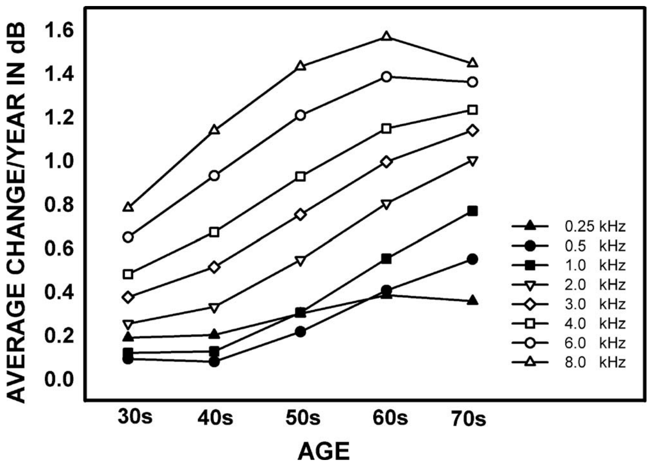


FIG. 4. The average estimated rate of change (in dB per year) of hearing thresholds as a function of age for each audiometric frequency.

kHz while approximately 80% of those in the 8th decade had hearing loss at this frequency. None of the men aged 30–39 had hearing loss at 0.25 kHz in contrast to nearly 30% of the men aged 70–79.

B. Rate of change

Based on the mixed-effects model, the annual rate of change of hearing thresholds over a ten-year interval was calculated. Figure 4 shows the average estimated annual rate for each age group for each frequency. The average rate of change per year across frequency and age was 0.69 dB (median=0.60, range=0.08–1.57). For 0.25 kHz, the rate varied little over the lifespan. For 0.5 and 1.0 kHz, the rate accelerated primarily over the 6th through 8th decades. For the frequency range 2.0–4.0 kHz, the rates increased roughly in a linear fashion through the 8th decade. For the frequencies of 6.0 and 8.0 kHz, the highest rate occurred in the 7th decade with subtle deceleration in estimated rates of change in the oldest men. The mean rate of change across decades was 0.29, 0.27, 0.37, 0.59, 0.75, 0.89, 1.11, and 1.27 dB per year for frequencies of 0.25–8.0 kHz, respectively. The mean rate of change collapsed across frequencies was 0.37, 0.50, 0.71, 0.90, and 0.98 for the 4th through 8th age decades, respectively. Overall, these findings suggest that the rates of change increase as frequency increases and that hearing loss accelerates with increasing age; however, rates of change vary as a function of frequency and age.

C. Cross-sectional and longitudinal comparison

Figure 5 gives a comparison of the average annual change in hearing thresholds based on the longitudinal trajectories described above and the trajectories based on a single cross-sectional view of the first visit data from each participant. The cross-sectional and longitudinal trajectories are consistent, with only minor differences between the trajectories, ≤ 0.26 dB (mean absolute difference=0.13, median=0.13, range=0.01–0.26 dB), for all frequencies for ages 30 through 60 years. However, the rates of change for frequencies of 2.0 kHz and above for the 70 year olds show that the cross-sectional data lead to a slight misestimate of

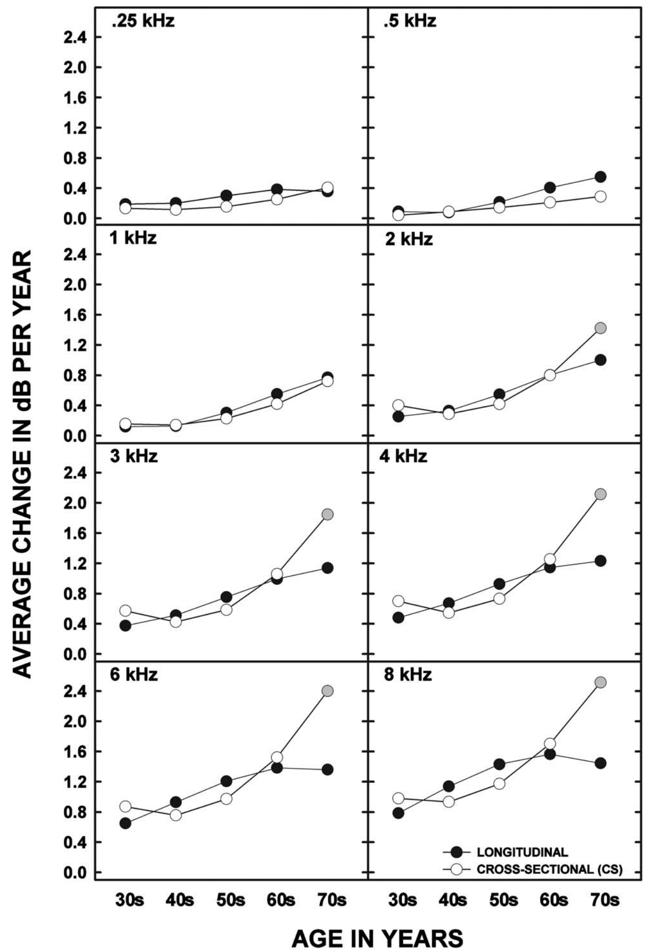


FIG. 5. The longitudinal (filled circles) and cross-sectional (CS; open circles) average annual rate of change (ordinate) of hearing threshold for each frequency as a function of age (abscissa). The gray-shaded circles for CS data at 2.0 through 8.0 kHz for the 70 year olds represent the larger differences in annual rates of change for this age group.

the average yearly change in hearing thresholds by as much as 1.07 dB at 8 kHz. For the 70 year olds, the differences between the cross-sectional and longitudinal annual rates of change were 0.42, 0.71, 0.88, 1.04, and 1.07 dB for frequencies of 2.0, 3.0, 4.0, 6.0, and 8.0 kHz, respectively, which are indicated in Fig. 5 with the gray symbols. The larger misestimations for the 8th decade may be a result of the cross-sectional data being based on fewer participants ($n=15$) with first visits in this age group relative to the other age groups. In summary, the average annual rates of change estimated from the cross-sectional and longitudinal threshold data overall are consistent across all frequencies for the 4th decade through the 7th decade, but the former misestimate the annual rates of change by ~1.0 dB for the 8th decade in the higher frequencies.

IV. DISCUSSION

This report describes the longitudinal progression of hearing loss for a large screened sample of men enrolled in the VA Normative Aging Study and joins a relatively sparse literature on longitudinal effects (Brant and Fozard, 1990; Gates *et al.*, 1990; Pearson *et al.*, 1995; Cruickshanks *et al.*,

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

2003; Wiley *et al.*, 2008). In this section, these findings are discussed, and related to the previous literature, including the BLSA. Some limitations of the current sample and analytic approach are considered and avenues for further research are suggested.

A. Hearing thresholds

The hearing thresholds of men who had no evidence of otologic pathologies or audiometric noise notches at any point during the study are reported. As with previous studies, the current results demonstrate that hearing thresholds are greatest for higher frequencies in older individuals and that hearing sensitivity for low frequencies was relatively preserved. The data from this study provide further evidence that changes in hearing thresholds were gradual and progressive and not limited to higher frequencies or to older age. The data, in fact, suggest that hearing loss, as indicated by thresholds greater than 25 dB HL, occurs at higher frequencies as soon as in the early 40s and at 3.0 and 4.0 kHz in the 50s.

Compared to the men in the BLSA sample, as reported by Pearson *et al.* (1995), the hearing sensitivity among the NAS sample was worse (by approximately 2 dB at lower frequencies and approximately 5 dB at higher frequencies). Given that both study samples were screened for otological disorders and evidence of noise-induced hearing loss in a similar fashion prior to the analysis, the somewhat poorer hearing thresholds of the NAS participants may result from differences between samples in exposure to noise and changing health conditions over the course of the study.

In relation to noise exposure, relative to the BLSA (8.1%), this NAS sample included greater numbers of men (23.1%) in occupations that may have involved exposure to excessive noise. It is plausible, however, that some men categorized as having traditionally noisy occupations (e.g., skill/craft, service, operatives) were assigned to positions with minimal or limited noise exposure (e.g., desk/administrative position). In contrast to the BLSA sample, where extent of military service is unknown, 88% of the NAS screened sample reported wartime military service. A significant proportion of men in the BLSA cohort also may have had military service histories, as was common for men in the early 20th century. A report evaluating threshold differences in veterans and non-veterans in the Beaver Dam Study sample, however, revealed no significant differences in thresholds at any frequency (Noe *et al.*, 2002). The history of recreational noise exposure for the current screened sample and for the BLSA sample is unknown. Because men in the NAS study enrolled at differing ages, some men with noise-induced hearing loss may have been included in the screened sample because they did not exhibit an audiometric noise notch while enrolled in the study.

Eligible participants in the NAS were screened for general physical health at their initial visit only, including self-reported hearing loss in both ears; however, the BLSA participants had no formal health criteria for inclusion until 1990 (Fozard *et al.*, 1990). Over the course of their participation, the NAS participants in the screened sample may have experienced health declines or developed other risk factors for hearing loss including cardiovascular disease, smoking, and ototoxic medication use (Wiley *et al.*, 2001), particularly at older ages and/or with greater number of study visits. Differences in the health screening and development of health conditions over time, therefore, may account for observed differences between the BLSA and NAS samples, particularly because the current NAS sample is based on the screened data of more participants (953 vs 681) with more times of measurement (3 478 vs 3 200 audiograms) and over a longer duration (periods up to 33 vs 23 years) than the BLSA report. While individuals were excluded from entry into the NAS if they were not in generally good physical health at that time, some participants in the screened sample had hearing loss (i.e., thresholds greater than 25 dB HL; see Fig. 2), because initial threshold level was not an exclusion criterion. Lastly, there were differences in the psychophysical procedures used for obtaining thresholds between the two studies. The NAS employed a bracketing procedure with 5-dB step sizes (Carhart and Jerger, 1959) whereas the BLSA employed the Bekesy psychophysical procedure, which provides greater measurement precision.

Lee *et al.* (2005), Wiley *et al.* (2001), Pearson *et al.* (1995), Ostri and Parving (1991), and others have compared their hearing threshold findings to the ISO-7029 standard that represents the aging thresholds for individuals with no otologic and noise-exposure histories. These authors, with the exception of Pearson *et al.* (1995), have reported that the ISO standards underestimate the thresholds found in their respective studies. This was the case even in a study for which participants were screened for a number of selected hearing loss risk factors (Wiley *et al.*, 2001). Pearson *et al.* (1995), however, found that the thresholds for the BLSA men generally were comparable to those in the ISO standard. The NAS hearing thresholds (observed and estimated) are mostly consistent with the ISO standard at the ages illustrated in Fig. 1; however, at the higher frequencies the estimated thresholds for participants in the 30s, 40s, and 50s are poorer than those in the ISO standard. These findings are in accord with other studies that have found the ISO standards to underestimate thresholds at the higher frequencies in middle age. The factors considered above, that may account for the differences between the BLSA and NAS thresholds reported here, also may account for the differences in thresholds between the NAS men and the ISO standards. In all, the observed thresholds are similar to the ISO-7029 Annex C median thresholds which, according to ANSI S3.44 (ANSI, 1996), are "identical" with the values in its Appendix A for men screened for otologic disease.

B. Annual rate of change

In the current study, the annual rate of threshold change was greatest for higher frequencies and was lowest for low frequencies. The rate of change at 0.25 kHz remained relatively stable with increasing age. The rate of change of thresholds between 0.50–4.0 kHz accelerated with increasing age. For the highest frequencies (6.0 and 8.0 kHz), the rates of change accelerated through the 7th decade then deceler-

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

ated at the oldest ages. These data are consistent with the rate of change data for men in the BLSA, reported by Pearson *et al.* (1995), and for men in the Framingham Heart Study, reported by Gates and Cooper (1991). On the other hand, the current data are contrary to findings from Wiley and colleagues (2008) and from Lee and colleagues (2005), who found that, for the older age groups, the rate of change among men was greater for low frequencies than for higher frequencies. The similarities in the rate of change data between the NAS men and the BLSA men may be due to the similarities between the screening of the two samples and the statistical methodologies. The rates of change from the NAS sample may differ from those for the Beaver Dam sample (Wiley *et al.*, 2008) because of the differences in statistical methods, and from those for the Lee *et al.* (2005) study owing to the shorter length of follow up and smaller sample size for the latter and differences in statistical methodologies. Overall the patterns of annual rates of change increase with increasing frequency and age, suggesting that aging differentially affects the portions of the auditory system responsible for low versus high frequency hearing (i.e., basal versus the apical portions of the cochlea); these effects remain to be understood fully. Generally, the impact that auditory risk factors have on age-related changes in hearing sensitivity likewise remains to be understood fully.

C. Longitudinal and cross-sectional estimate comparisons

Longitudinal studies enable the direct measurement of change with aging. Consequently, investigations of how hearing sensitivity changes across the lifespan are best accomplished using longitudinal approaches (Brant and Pearson, 1994). Cross-sectional estimates of hearing sensitivity, however, are easier to obtain than longitudinal measurements. A goal of the current study was to compare these two types of estimates over a 10-year period. The findings (see Fig. 5) suggest that cross-sectional measures of average threshold change in dB per year slightly misestimate the longitudinal trajectories as a function of age and frequency, at least in a screened sample of men. The mean absolute value of the difference in annual rates of change between cross-sectional and longitudinal estimates of hearing levels averaged across frequency and age after 10 years in this study is 0.21 dB (median=0.14, range=0.01–1.07 dB), which is smaller than that reported by Pearson *et al.* (1995) at 3.5 dB. The extent to which cross-sectional trajectories approximate longitudinal trajectories may depend on the degree to which longitudinal study participants, if not screened on a continual basis, subsequently develop diseases or risk factors that could affect hearing and would be most prevalent at older ages. Overall, based on the findings of the BLSA and the current report with NAS data, hearing levels predicted from cross-sectional data may generally well approximate hearing levels estimated from longitudinal data.

V. SUMMARY AND CONCLUSIONS

This report documents longitudinal changes in hearing sensitivity in a large screened sample of men and joins a relatively sparse literature on hearing loss progression with aging (Brant and Fozard, 1990; Gates *et al.*, 1990; Pearson *et al.*, 1995; Cruickshanks *et al.*, 2003; Wiley *et al.*, 2008). These results indicate that initially healthy men accrue marked losses in hearing sensitivity for higher frequencies as early as in their late 40s; demonstrate declines in hearing sensitivity for the mid-range frequencies (2.0, 3.0, 4.0 kHz) in their mid 50s to the late 60s; and maintain hearing sensitivities that are better than 25 dB HL at the lower frequencies (0.25, 0.5, and 1.0 kHz) into old age. The rates of change accelerate across frequency and age with modest deceleration at the oldest ages and highest frequencies (6.0 and 8.0 kHz). Cross-sectional estimates of change in hearing sensitivity approximate the longitudinal trajectories for all frequencies and at most ages reliably, but may yield slight misestimates at ages 70 and higher, particularly at higher frequencies.

The thresholds from the current sample, although highly screened for evidence of otologic pathology and noise-induced hearing loss, are slightly poorer than thresholds reported from BLSA men modeled using the same approach, and than those in the ISO standard. Because pure presbycusis is rare in industrialized societies and noise exposure in daily life is increasingly commonplace, even among demographically advantaged individuals, future research to disentangle the mechanisms and impact of risk factors on age-related hearing changes may employ different exclusion criteria to facilitate greater generalizability to modern aging populations.

ACKNOWLEDGMENTS

This research was supported by the Department of Veterans Affairs, Veterans Health Administration, Office of Research and Development, Rehabilitation Research and Development (RR&D) Service Merit Review Award (no. O3494R) to the first and last authors and provided support for the third author. The second author is supported by an VA RR&D Research Career Development Award (no. C3529V) and by the Auditory and Vestibular Dysfunction Research Enhancement Award Program (REAP) sponsored by VA RR&D (no. C4339F). Support to the last author is also provided by a VA Clinical Sciences Research and Development (CSR&D) Merit Review and by a VA CSR&D Research Career Scientist Award. The contents do not necessarily represent the views of the U.S. Department of Veterans Affairs or the United States Government. The authors gratefully acknowledge the time and contributions of the reviewers and the associate editor on earlier versions of this manuscript. The VA Normative Aging Study (NAS) is supported by VA Cooperative Studies Program/ERIC and is a research component of the Massachusetts Veterans Epidemiology Research and Information Center (MAVERIC). We thank the men of the VA NAS for their generous contributions of time and effort to our research over the past 45+ years.

American Standards Association (**1951**). *American Standard Specification for Audiometers for General Diagnostic Purposes* (American Standards Association, New York), Pub. no. 224.5-1951.

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp

ANSI (**1969**). *ANSI S3.6–1969; Specifications for Audiometers* (American National Standards Institute, New York).

ANSI (**1989**). *ANSI S3.6–1989; American National Standard Specification for Audiometers* (American National Standards Institute, New York).

ANSI (**1996**). *ANSI S3.44; Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment* (American National Standards Institute, New York).

Bell, B., Rose, C. L., and Damon, A. (**1972**). "The normative aging study: An interdisciplinary and longitudinal study of health and aging," Int. J. Aging Hum. Dev. **3**, 5–17.

Bossé, R., Ekerdt, D., and Silbert, J. (**1984**). "The veterans administration Normative Aging Study," in *Handbook of Longitudinal Research*, edited by S. A. Mednick, M. Harway and K. Finello (Praeger, New York), Vol **2**, pp. 273–295.

Brant, L. J., and Fozard, J. L. (**1990**). "Age changes in pure-tone thresholds in a longitudinal study of normal human aging," J. Acoust. Soc. Am. **88**, 813–820.

Brant, L. J., and Pearson, J. D. (**1994**). "Modeling the variability in longitudinal patterns of aging," in *Biological Anthropology and Aging*, edited by D. E. Crews and R. M. Garruto (Oxford, New York), pp. 374–393.

Carhart, R., and Jerger, J. F. (**1959**). "Preferred method for clinical determination of pure-tone thresholds," J. Speech Hear Disord. **16**, 340–345.

Cooper, J. C., Jr. (**1994**). "Health and nutrition examination survey of 1971–1975: Part I. Ear and race effects in hearing," J. Am. Acad. Audiol **5**, 30–36.

Corso, J. F. (**1958**). "Proposed laboratory standard of normal hearing," J. Acoust. Soc. Am. **30**, 14–23.

Cruickshanks, K., Wiley, T., and Tweed, T. (**1998**). "Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin: The epidemiology of hearing loss study," Am. J. Epidemiol. **148**, 879–886.

Cruickshanks, K. J., Tweed, T. S., Wiley, T. L., Klein, B. E. K., Klein, R., Chappell, R., Nondahl, D. M., and Dalton, D. S. (**2003**). "The five-year incidence of hearing loss: The epidemiology of hearing loss study," Arch. Otolaryngol. Head Neck Surg. **129**, 1041–1046.

Damon, A. (**1969**). "Medical criteria for acceptance into the normative aging study: Five domain report," Technical report of the Normative Aging Study, VA Outpatient Clinic, Boston, MA.

Davis, A. C., Ostri, B., and Parving, A. (**1991**). "Longitudinal study of hearing," Acta Oto-Laryngol., Suppl. **111**, 12–22.

Divenyi, P. L., and Simon, H. J. (**1999**). "Hearing in aging: Issues old and young," Audiology **7**, 282–289.

Fozard, J. L., Metter, E. J., and Brant, L. J. (**1990**). "Next steps in describing aging and disease in longitudinal studies," J. Gerontol. **45**, 116–127.

Gates, G. A., and Cooper, J. C. (**1991**). "Incidence of hearing decline in the elderly," Acta Oto-Laryngol. **111**, 240–248.

Gates, G. A., Cooper, J. C., Kannel, W. B., and Miller, N. J. (**1990**). "Hearing in the elderly: The Framingham cohort, 1983–1985: Part I. Basic audiometric test results," Ear Hear. **11**, 247–256.

Goldstein, H. (**1995**). *Multilevel Statistical Models* (Edward Arnold, London), pp. 16–20.

Helzner, E. P., Cauley, J. A., Pratt, S. R., Wisniewski, S. R., Zmuda, J. M., Talbott, E. O., de Rekeneire, N., Harris, T. B., Rubin, S. M., Simonsick, E. M., Tylavsky, F. A., and Newman, A. B. (**2005**). "Race and sex differences in age-related hearing loss: The health, aging, and body composition study," J. Am. Geriatr. Soc. **53**, 2119–2127.

Hietanen, A., Era, P., Sorri, M., and Heikkinen, E. (**2004**). "Changes in hearing in 80-year-old people: A 10-year follow-up study," Int. J. Audiol. **43**, 126–135.

Hirsh, I. J. (**1952**). *Measurement of Hearing* (McGraw-Hill, New York), pp. 1–364.

ISO (**1964**). *ISO/R389–1964; Standard Reference Zero for the Calibration of Pure Tone Audiometers* (International Organization for Standardization, Switzerland).

ISO (**2000**). *ISO-7029: Acoustics Statistical Distribution of Hearing Thresholds as a Function of Age* (International Organization for Standardization, Switzerland).

Kochkin, S. (**2005**). "MarkeTrak VII: Hearing loss population tops 31 million people," Hear. Rev. **12**, 16–29.

Kryter, K. D. (**1985**). *The Effects of Noise on Man*, 2nd ed. (Academic, New York), pp. 1–688.

Lawrence, H., Garcia, R., Essick, G., Hawkins, R., Krall, E., Spiro, A., Vokonas, P. S., Kong, L., King, T., and Koch, G. G. (**2001**). "A longitudinal study of the association between tooth loss and age-related hearing loss," Spec Care Dentist **21**, 129–140.

Lee, F. S., Matthews, L. J., Dubno, J. R., and Mills, J. H. (**2005**). "Longitudinal study of pure-tone thresholds in older persons," Ear Hear. **26**, 1–11.

Lethbridge-Cejku, M., Schiller, J. S., and Bernadel, L. (**2004**). "Summary health statistics for U.S. adults: National Health interview survey, 2002," Vital Health Stat. **222**, 1–151.

Moller, M. B. (**1981**). "Hearing in 70 and 75 year old people: Results from a cross-sectional and longitudinal population study," Am. J. Otolaryngol. **2**, 22–29.

Mościcki, E. K., Elkins, E. F., Baum, H. M., and McNamara, P. M. (**1985**). "Hearing loss in the elderly: An epidemiologic study of the Framingham heart study cohort," Ear Hear. **6**, 184–190.

Nelson, E. G., and Hinojosa, R. (**2006**). "Presbycusis: A human temporal bone study of individuals with downward sloping audiometric patterns of hearing loss and review of the literature," Laryngoscope **116**, 1–12.

Noe, C. M., Cruickshanks, K. J., Nondahl, D., Wiley, T. L., and Wilson, R. H. (**2002**). "Prevalence of hearing loss among the veteran population in the Beaver Dam (WI) cohort," in ASHA Convention, Atlanta, GA, April.

Ostri, B., and Parving, A. (**1991**). "A longitudinal study of hearing impairment in male subjects—an 8-year follow-up," Br. J. Audiol. **25**, 41–48.

Pearson, J. D., Morrell, C. H., Gordon-Salant, S., Brant, L. J., Metter, E. J., Klein, L. L., and Fozard, J. L. (**1995**). "Gender differences in a longitudinal study of age-associated hearing loss," J. Acoust. Soc. Am. **97**, 1196–1205.

Pedersen, K. E., Rosenhall, U., and Moller, M. B. (**1989**). "Changes in pure-tone thresholds in individuals aged 70–81: Results from a longitudinal study," Audiology **28**, 194–204.

Singer, J. D., and Willett, J. B. (**2003**). *Applied Longitudinal Data Analysis: Modeling Change and Event Occurrence* (Oxford University Press, New York), pp. 138–188.

Ward, W. D. (**1980**). "Noise-induced hearing damage," in *Otolaryngology*, edited by M. Paparella and D. Shumrick (Saunders, Philadelphia), Vol. **III**, pp. 1788–1803.

Wiley, T. L., Chappell, R., Carmichael, L., Nondahl, D. M., and Cruickshanks, K. J. (**2008**). "Changes in hearing thresholds over 10 years in older adults," J. Am. Acad. Audiol **19**, 281–292.

Wiley, T. L., Torre, P. III, Cruickshanks, K. J., Nondahl, D. M., and Tweed, T. S. (**2001**). "Hearing sensitivity in adults screened for selected risk factors," J. Am. Acad. Audiol **12**, 337–347.

Downloaded 18 Oct 2010 to 170.140.223.91. Redistribution subject to ASA license or copyright; see http://asadl.org/journals/doc/ASALIB-home/info/terms.jsp